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# Semiannual Technical Summary

# Seismic Discrimination

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LINCOLN LABORATORY

# SEISMIC DISCRIMINATION

SEMIANNUAL TECHNICAL SUMMARY REPORT
TO THE
ADVANCED RESEARCH PROJECTS AGENCY

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## ABSTRACT

Detailed studies of short-period characteristics of explosive sources on a global basis have been completed. Substantial effort has been expended in the study of propagation path phenomena, aimed at the understanding of discriminant capabilities and limitations at low magnitudes. LASA data have been used for several projects involving the detailed characteristics of seismic waves from explosions and earthquakes. A continuous improvement in our data facilities and automatic processing capabilities is reported.



Accepted for the Air Force
Jerome E. Horowitz
Acting Project Officer

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## SUMMARY

This is the thirteenth Semiannual Summary of work done by Lincoln Laboratory for the Advanced Research Projects Agency under Project VELA, the aim of which is to establish a basis for the identification of underground nuclear explosions.

Work has recently been completed on the nature of the seismic signal from events in the Soviet Union at a known test site. In order to put further factual basis behind the short-period spectral discriminants we have used, comparisons have been made between theoretical models of explosions and spectral characteristics across a range of magnitude from 5.4 to 6.1. Although many features seem predictable, lateral variations in attenuation in the mantle are substantial and need careful allowance for any predictive scheme for signal character. Studies of NTS events have been pursued in two directions. The survey of ultra-long-period spectral characteristics has been completed and the remarkable notch in the coherency of the signal at 0.02 Hz has continued to show itself. There appears to be continued promise in short-period spectral discrimination, so a collection of regional observations of NTS events is being made for this purpose.

A large amount of research has been devoted to the problem of seismic observations in a laterally heterogeneous Earth. The evidence on such heterogeneities is growing steadily and is frequently connected with aspects of plate tectonics. It can be demonstrated that severe alterations in signal shape can be the consequence of underthrust lithospheric slabs, as clearly revealed by our study of Longshot. We have re-examined the role of complexity in such a situation and find that its value as a discriminant may be higher than previously thought. The LASA bulletin is now produced automatically and it is a matter of some interest to know whether the location process is affected seriously by these heterogeneities which could affect $dT/d\Delta$ observations at LASA. Preliminary results show that much of the scatter in location in some areas can be attributed to near-source structure. High quality array data also allow us to begin to understand gross heterogeneities in absorption of seismic waves. A study of spectral characteristics of seismic signals is revealing such variations in Q. A major study of the composition of the Rayleigh wave signal in terms of direction of approach and delay time has been completed and shows striking multipath propagation which may be attributed to continental margin and midocean ridge effects. Analysis of surface waves for discrimination needs some indication of the potential amplitude variations these phenomema imply; for this reason, and also to study wave propagation in the vicinity of underthrust plates, a general purpose ray tracing program has been developed and the first results from it are shown.

Attention has been given to aspects of array processing which may be exploited where single seismometers are of no use. In particular, we are looking at coherence in signal and its implications. Even underground explosions seem to be somewhat incoherent across the array and it is fairly clear that this incoherence is not entirely attributable to sub-LASA structure, since it is possible to find extremely coherent earthquakes. The power of VESPA (a display of energy in incident angle time space) at picking up small signals in the P-wave coda is strikingly demonstrated in terms of reflections from upper mantle discontinuities. Studies are continuing on the ability of VESPA to deal with multiple signals from different events.

Further analysis of the frequency-wavenumber spectral estimation used in many of our studies has led to exact probability distributions for the estimators. A study of the relative merits of the maximum entropy, maximum likelihood and conventional methods of power spectral density estimation has been completed.

Our console analysis facilities have been substantially upgraded and allow the study of a much larger set of data than previously. In addition, programs which are central to routine analysis of seismic data are steadily being made available on the PDP-7 computers for immediate use to avoid the expensive and time-consuming need to process much of our data at the M.I.T. Computation Center. With the arrival of more NORSAR data and the acquisition of a large amount of worldwide standard network film material, we intend to broaden the basis of our discrimination techniques.

D. Davies

GLOSSARY

| | |
|---|---|
| ARPA | Advanced Research Projects Agency |
| DART | Digital Acquisition Recording Terminal |
| LASA | Large Aperture Seismic Array, Billings, Montana |
| NORSAR | Norwegian Seismic Array |
| NTS | Nevada Test Site |
| SAAC | Seismic Array Analysis Center, Washington, D. C. |
| SATS | Semiannual Technical Summary |
| TFSO | Tonto Forrest Seismic Observatory |
| UKAEA | United Kingdom Atomic Energy Authority |
| USCGS | United States Coast and Geodetic Survey |
| VESPA | Velocity Spectral Analysis |
| YKA | Yellowknife Seismic Array, Canada |

## SEISMIC DISCRIMINATION

# I. SOURCE STUDIES

## A. USE OF SHORT-PERIOD DATA TO EXAMINE EXPLOSIVE SOURCE CHARACTERISTICS

In the previous SATS,[1] Filson studied the short-period spectra of four presumed Soviet explosions from eastern Kazakh recorded at five widely separated arrays. Spectral analysis of the steered array sum of each event was inconclusive for estimating consistent burial depths of each presumed shot. However, spectral ratios of high-to-low-magnitude beamed events verified the relative attenuation of high frequencies with increasing magnitude predicted by Haskell.[2]

A new study of the same four events has been made at LASA using the deep hole seismometer traces at each subarray rather than the steered beam of the same traces. The purpose of this was to see if consistent transfer functions from low to high magnitude events could be determined at each LASA site, and if possible interpret such transfer functions in terms of the far field displacement velocity response of a spherical cavity given by Blake.[3]

Figure I-1 shows records of the four presumed explosions taken from the F- and E-rings of LASA. The events are arranged in order of increasing LASA magnitude from left to right. The plotted amplitude of each event was adjusted to remove the differences in LASA magnitude, whereas the relative amplitudes from site to site for each event were preserved.

Transfer functions were computed at each subarray site to shape the low magnitude events (1, 2, and 4) to the highest magnitude event, no. 5. Since these events were closely located,[1] source to receiver effects such as attenuation, spherical spreading, ray distortion in the mantle and crust, and instrument response, should be common to pairs of events recorded at the same site. This is apparent from Fig. I-1, which shows considerably more coherence from event to event at the same site, than for a given event recorded at different sites.

Under the assumptions above, the transfer function for each pair of events should only reflect differences in the source spectra, all other propagation effects canceling out. Let $E_{ik}(t)$ be event i as recorded by subarray site k. In the frequency domain we define the transfer function $R_{ijk}(w)$ as the spectral ratio

$$R_{ijk}(w) = \frac{E_{jk}(w)}{E_{ik}(w)} \cong \frac{S_j(w)}{S_i(w)} \tag{1}$$

at site k, where $S_j(w)$ is the source spectrum of event j.

Figures I-2, I-3, I-4 show the calculated transfer functions $R_{15k}$, $R_{25k}$, and $R_{45k}$ for the available LASA subarray sites. These filters were computed in the time domain by a least-squares technique so that they contain both amplitude and phase information in the frequency domain. Index k runs from 1 to 21 corresponding to the subarray F1, F2, ... E1, E2, ... A0, respectively. In each figure the boxed filter $\overline{R}_{ij}$ is the average of the individual filters for each pair of events.

An interesting feature is the coherence of the transfer functions from site to site despite the extreme variations in shape and amplitude of the recorded events. This site-to-site coherence improves as the magnitude of the denominator event in Eq. (1) increases, probably due to the increased signal-to-noise ratio of the data.

An attempt was made to explain the gross features of the averaged filters by taking as an explosion source model a cavity of radius $a_i$ in a homogeneous medium of velocity c. Assuming that the cavity is excited by a step function of pressure p, which is independent of cavity size, the far-field displacement velocity field is given by Blake.[3] For events from a common test site recorded at a given site, Blake's far-field solution, taken as the source function, can be written as

$$S_i(t) = kpa_i e^{-\alpha_o t} \cos(w_o t + \phi) \quad , \tag{2}$$

where $\alpha_o$ and $w_o$ are proportional to $c/a_i$, k is a constant, and $\phi$ depends only on Poisson's ratio $\sigma$.

For large magnitude explosions in hard rock there is evidence[4] that the equivalent elastic cavity radius varies as the cube root of the yield, which is proportional to amplitude. Using the relative magnitudes of the four events at LASA, cavity radii at the source for the three smaller events can be scaled down from $a_5$. For an explosion of magnitude 6.1 in hard rock, the yield and equivalent cavity radius have been estimated[4] to be ~ 100 kt and ~ 700 m, respectively. Table I contains two sets of scaled radii for the events assuming $a_5$ = 500 and 750 m separately. Figure I-5 shows a graph of Eq. (2) for the second set of scaled radii in Table I, assuming c = 5 km/sec, and $\sigma$ = 0.3.

TABLE I

SCALING OF CAVITY RADII FROM LASA MAGNITUDES FOR FOUR PRESUMED EXPLOSIONS FROM EASTERN KAZAKH

| Event | $m_b$ (LASA) | $a_i/a_5$ | $a_i$(m) Assuming $a_5$ = 500 | $a_i$(m) Assuming $a_5$ = 750 |
|---|---|---|---|---|
| 1 | 5.4 | 0.585 | 293 | 438 |
| 2 | 5.6 | 0.681 | 341 | 511 |
| 4 | 5.8 | 0.781 | 391 | 586 |
| 5 | 6.1 | 1.000 | 500 | 750 |

Theoretical transfer functions $\widetilde{R}_{ij}(t)$ defined in the frequency domain by

$$\widetilde{R}_{ij}(w) = S_j(w)/S_i(w) \tag{3}$$

were computed in the time domain for both sets of cavity radii. These theoretical filters are plotted with the averaged empirical filters $\overline{R}_{ij}$ in Fig. I-6.

It appears that the theoretical filters $\tilde{R}_{ij}(t)$ for the second set of radii ($a_5$ = 750 m) fit the empirical filters $\bar{R}_{ij}$ somewhat better than the first set. An improvement of fit could be obtained by low-pass filtering the theoretical filters to round off their spikes.

In conclusion, there seems to be consistent differences between the source functions of low and high magnitude presumed explosions. The explanation provided here using Blake's results seems satisfactory even though it ignores coupling between the source cavity and the free surface. However, the method could be checked by applying the same analysis to NTS shots of known yield and depth recorded at other arrays such as NORSAR.

C. W. Frasier

The use of the worldwide array data described in the last SATS has been extended. Figure I-7 shows the normalized velocity spectra computed from 10 seconds of the P-wave beam from five events in central Asia and recorded at five arrays (Oslo, Norway; Warramunga, Australia; Gauribidanur, India; Yellowknife, Canada; and LASA). The events are presumed to be explosions. The USCGS locations of 4 of the five events are tightly grouped and the magnitudes ($m_b$) given are 1-5.3, 2-5.2, 3-5.4, 4-5.4 to 5.5 (author's estimate) and 5-5.7; event 4 not having been reported by USCGS. Events 1, 2, 4, and 5 are the same as discussed by Frasier in this report; however, his magnitudes are based on LASA amplitudes.

The salient feature of Fig. I-7 is that there appears to be a shift in energy toward lower frequencies with increasing magnitude. This feature is particularly evident when event 1 is compared with event 5 at all array sites except YKA. In an attempt to quantify this phenomenon, Haskell's[2] model for the contained explosion spectrum has been fitted to each observed spectrum in the following manner. By using Eq. (4),

$$G = \sum_{j=1}^{N} [D(f_j)\, e^{+\pi f_j t^*} - H(\alpha, \beta, k, f_j)]^2 \tag{4}$$

the quantity G is minimized over the frequency ($f_j$) band 0.6 to 3.0 Hz. In Eq. (4) $D(f_j)$ represents the observed spectrum corrected for instrument response, $t^*$ is an attenuation parameter, H is Haskell's function with $\alpha$ dependent on the medium, $\beta$ depends upon the medium and the cube root of the yield, and k depends on the medium and is directly proportional to the yield. Since $t^*$ is considered unknown, G is minimized for all the events at a single site for various values of $t^*$ and that value of $t^*$ which yields the parameters $\beta$ and k varying most closely to the cube root scaling law for all the events is chosen as the best estimate of $t^*$. Once the estimate of $t^*$ is made at each array, a single source model is fitted simultaneously to all the spectra of a given event. The results of the individual and simultaneous fitting procedures are given in Table II. The values of effective Q ($Q_E$ = travel time divided by $t^*$) are also given in the table; the value of $Q_E$ at YKA is essentially undetermined by this method. The method assumes that the properties of the source medium do not vary greatly from event to event.

Obviously results from such a technique cannot be taken as a simultaneous verification of an assumed source model and absolute determination of the attenuative properties of the earth, but it does allow quantification of spectral contrasts observed between different events at the

TABLE II

ESTIMATES OF SEISMIC PARAMETERS AT FIVE ARRAYS

| Site | $Q_E \approx$ | Norway 8000 | Australia 3600 | India 2000 | Canada (multi-site estimate) | LASA 1600 | $\sum$ |
|---|---|---|---|---|---|---|---|
| 1 | α | 6.8 | 6.8 | 6.7 | 8.1 | 6.8 | 6.7 |
| | β | 0.42 | 0.53 | 0.59 | 0.71 | 0.57 | 0.53 |
| 2 | α | 6.8 | 6.6 | No data | 6.7 | 6.7 | 6.2 |
| | β | 0.42 | 0.67 | | 0.64 | 0.52 | 0.51 |
| 3 | α | No data | 8.6 | 6.7 | 6.7 | 6.8 | 7.0 |
| | β | | 0.56 | 0.58 | 0.66 | 0.44 | 0.54 |
| 4 | α | No data | 6.9 | 6.7 | 6.8 | 6.7 | 6.9 |
| | β | | 0.48 | 0.63 | 0.55 | 0.59 | 0.57 |
| 5 | α | 6.7 | 6.5 | 6.5 | 6.7 | 6.7 | 6.4 |
| | β | 0.59 | 0.86 | 0.73 | 0.62 | 0.63 | 0.67 |

same site and the same event at different sites. Coincidentally or not, the values of $t^*$ determined increase with array size, the beam-forming procedure apparently attenuating the higher frequencies. Alternatively, beamforming decreases the incoherent noise and will probably be used if such techniques are extended to lower magnitudes.

In Fig. I-8, using the values of $\beta$ determined in the simultaneous fit (listed under $\Sigma$ in Table II), the quantity $\log_{10}(\beta^3)$ is plotted against USCGS $m_b$. As previously stated $\beta^3$ should be proportional to yield and in Fig. I-8, $\log_{10}(\beta^3)$ vs $m_b$ is compared with a line of slope 1.0.

In conclusion, there appears to be, whether the quantification technique used is an optimum one or not, the strong suggestion of information concerning the nature of the explosive source in the short-period spectrum as observed at teleseismic distances.

J. R. Filson

## B. AMPLITUDE MEASUREMENTS OF NTS EVENTS AT LASA

In order to study distribution of energy into body and surface waves from explosive sources, a study of NTS events using LASA data has been initiated. At present only preliminary measurements have been made and they are reported without interpretation. Figure I-9 shows the results of $P_n$ and Rayleigh wave measurements taken at LASA A0 from 13 NTS announced explosions. The $P_n$ measurements were made on the maximum amplitude of short-period vertical data recorded within 3 seconds of the initial arrival. This phase, in most cases, has a period of 1.5 seconds. The Rayleigh wave measurements were made from the long-period vertical instrument at AO on a phase that had a period of about 16 seconds. Although this phase was usually not the maximum amplitude recorded (a phase of about a 10-second period was larger) it was used because of clipping of the larger phase from the events of higher magnitude. The amplitudes reported in Fig. I-9 have been corrected for instrument response and are based on half the trough-to-peak measurements. Different media for the shot location will be separately studied as this survey expands.

J. R. Filson

## C. LONG- AND ULTRA-LONG-PERIOD CHARACTERISTICS OF NTS EVENTS RECORDED AT LASA

Analysis of the vertical motion of NTS events recorded at LASA has shown that the wavenumber spectra indicate a lack of coherent propagation at 0.02 Hz, but that coherent propagation exists at lower frequencies.[1] Further studies since the last report have failed to detect very low frequency propagation at LASA from NTS events with body-wave magnitudes (USCGS) less than 5.2. All events which were analyzed and had an $m_b$ greater than 5.2 exhibit the notch at 0.02 Hz in the frequency-wavenumber spectrum. For some events (e. g., Zaza, Sled, Lanpher) this notch coincides with a dip in the power spectrum. However, other events (e.g., Purse, Faultless) show no such agreement between the two kinds of spectra.

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3. F. G. Blake, "Spherical Wave Propagation in Solid Media," J. Acoust. Soc. Am. 24, 211-215 (1951).

4. D. Davies (rapporteur), "Seismic Methods for Monitoring Underground Explosions" published by SIPRI, Stockholm (1968).

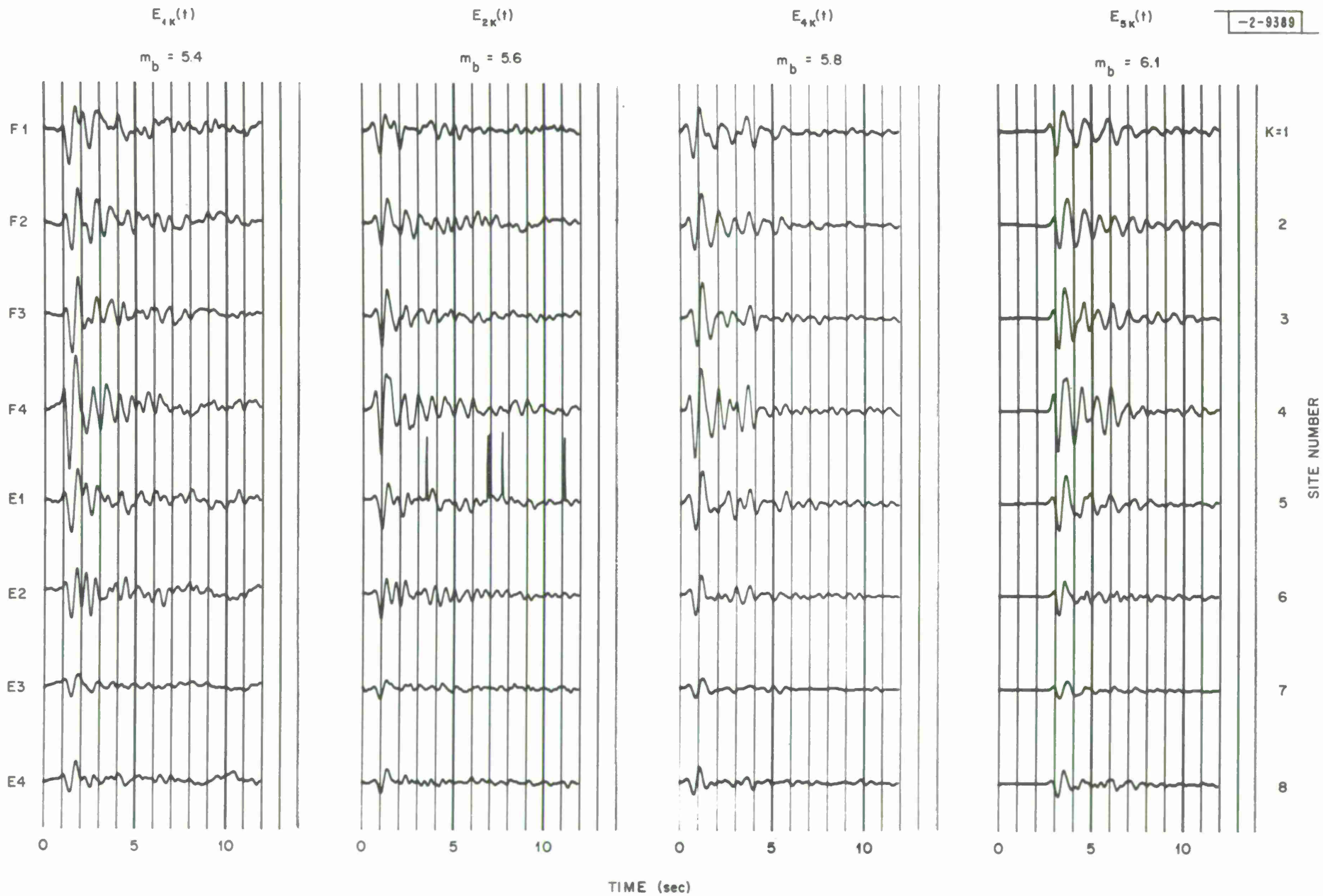


Fig. I-1. LASA records of four presumed explosions from eastern Kazakh. They are arranged in order of increasing LASA magnitude from left to right.

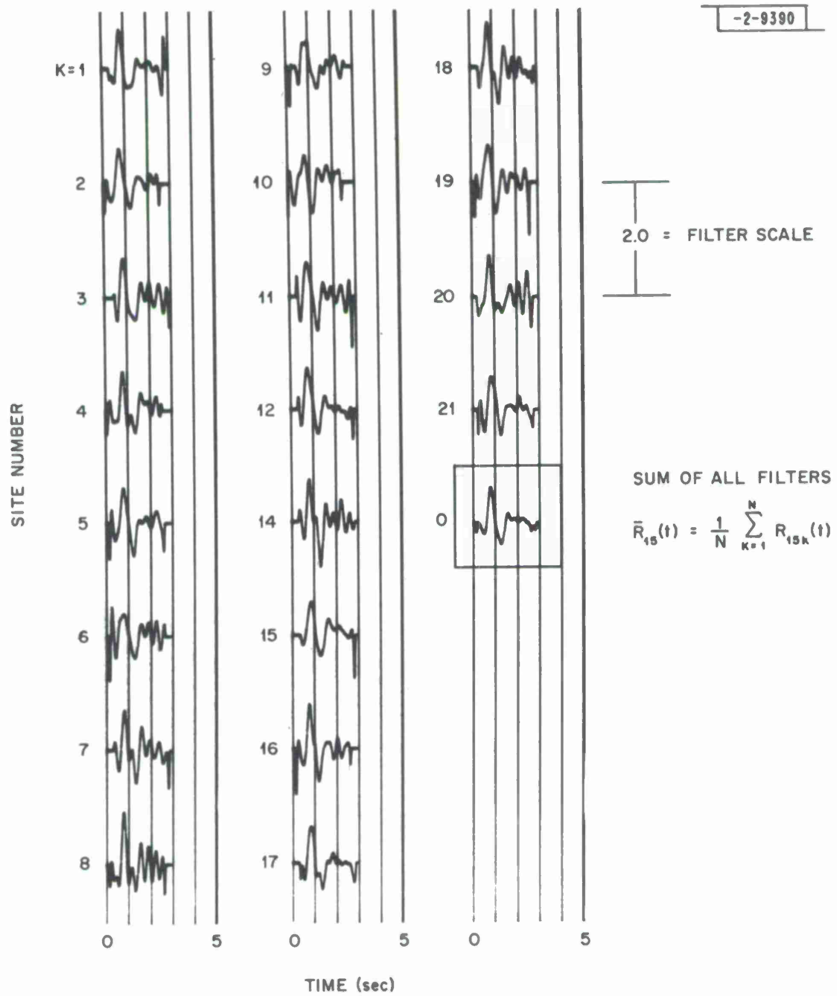


Fig. I-2. Empirical transfer functions $R_{15k}(t)$ to shape event 1 to event 5 at subarray site k. Average of all filters is shown in box.

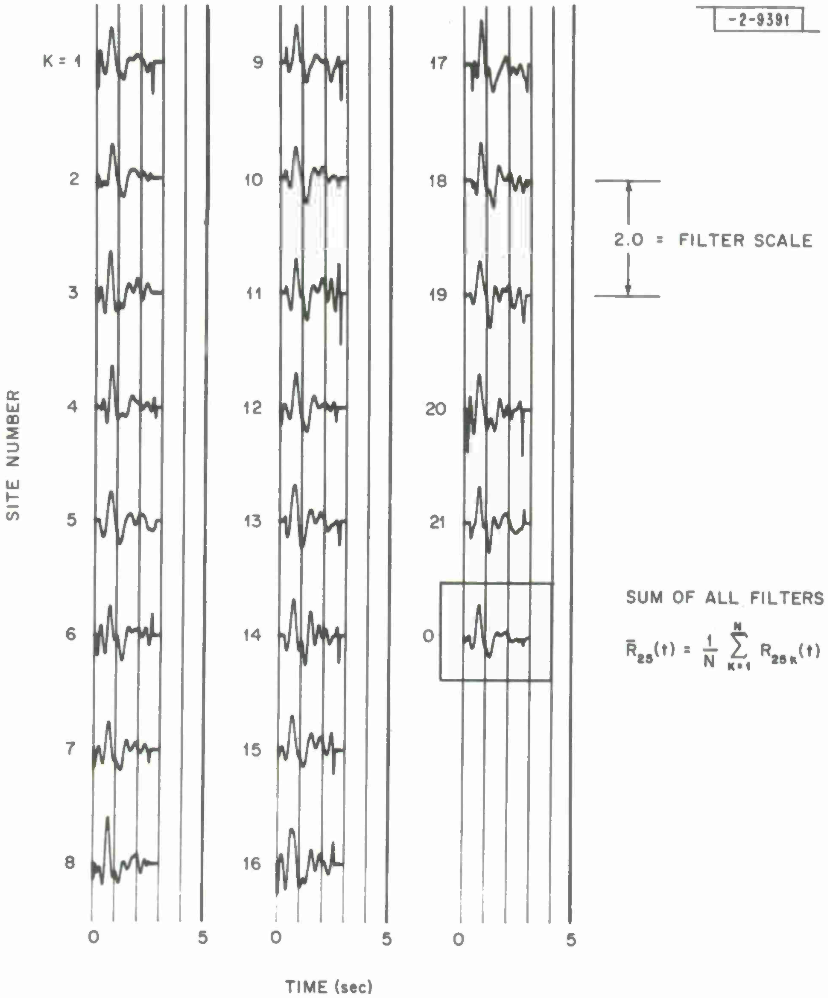


Fig. I-3. Empirical transfer functions $R_{25k}(t)$ to shape event 2 to event 5 at subarray site k. Average of all filters is shown in box.

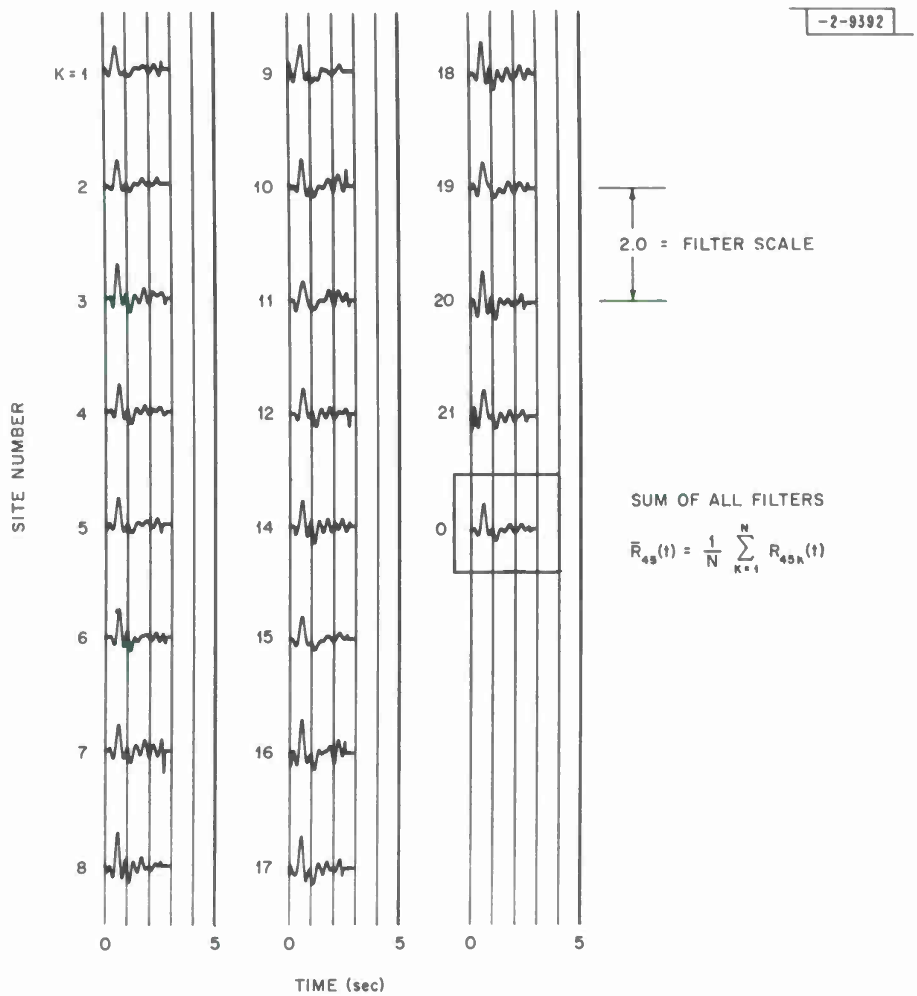


Fig. I-4. Empirical transfer functions $R_{45k}(t)$ to shape event 4 to event 5 at subarray site k. Average of all filters is shown in box.

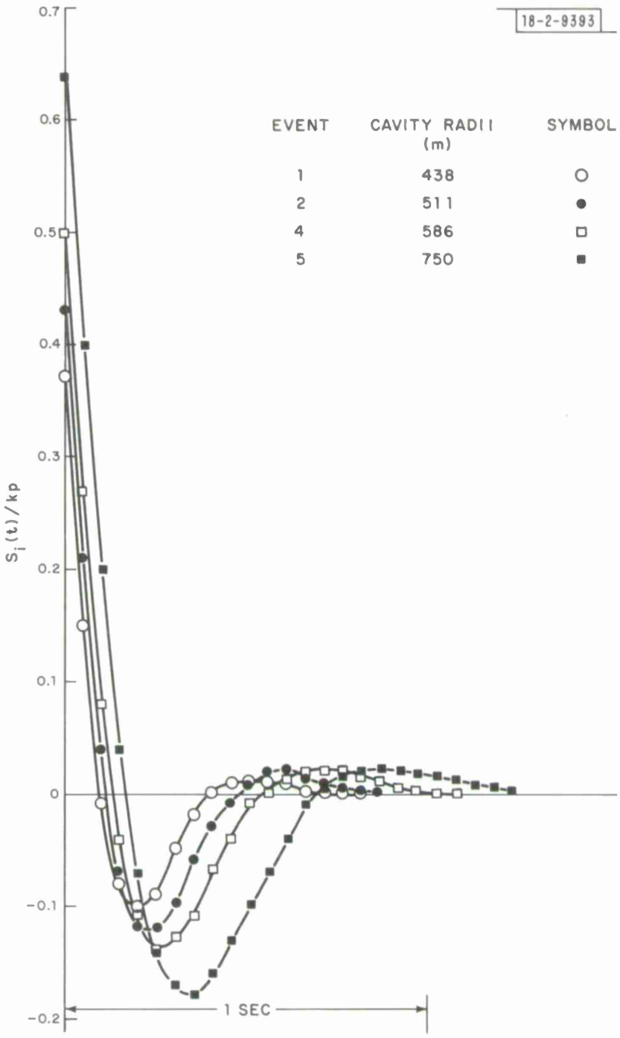


Fig. I-5. Blake's displacement velocity for the second set of cavity radii in Table I. Parameters common to all curves are c = 5 km/sec and $\sigma = 0.3$.

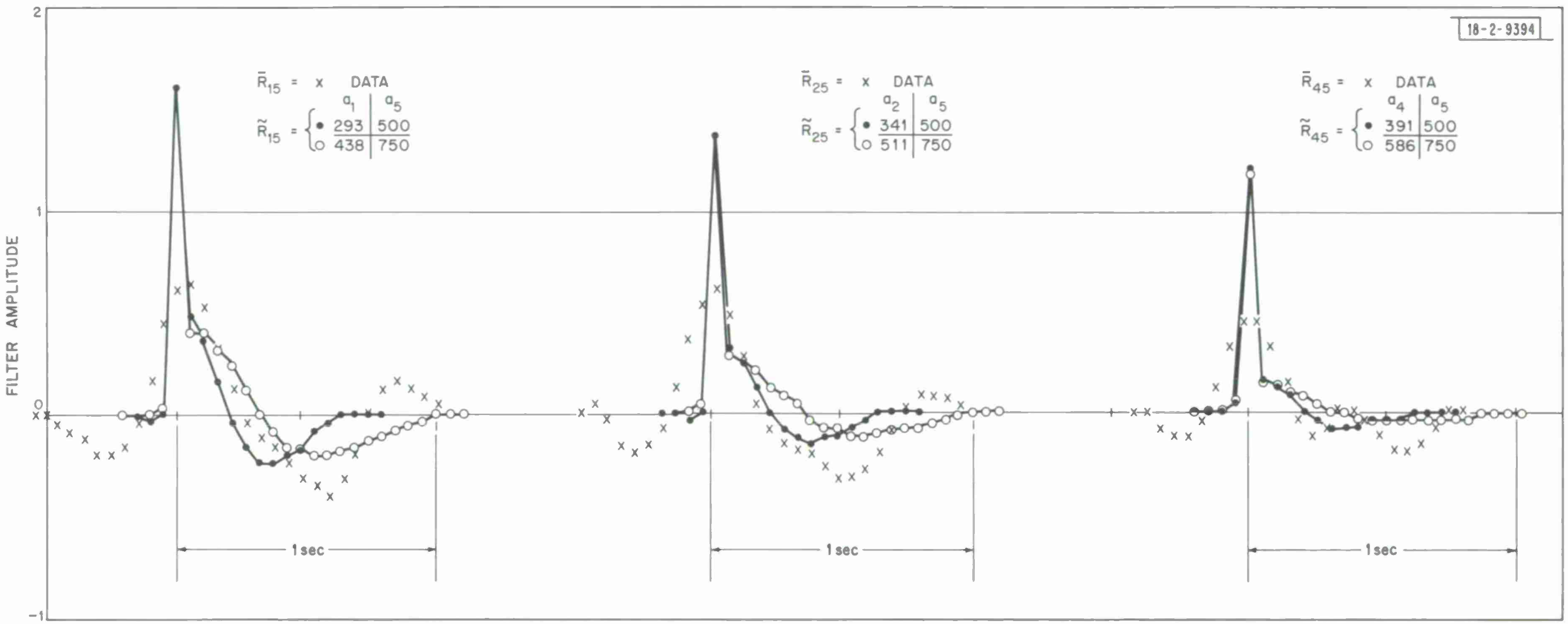


Fig. I-6. Comparison of observed transfer functions $\bar{R}_{ij}$ and theoretical transfer functions $\tilde{R}_{ij}$ for shaping low magnitude to high magnitude explosions.

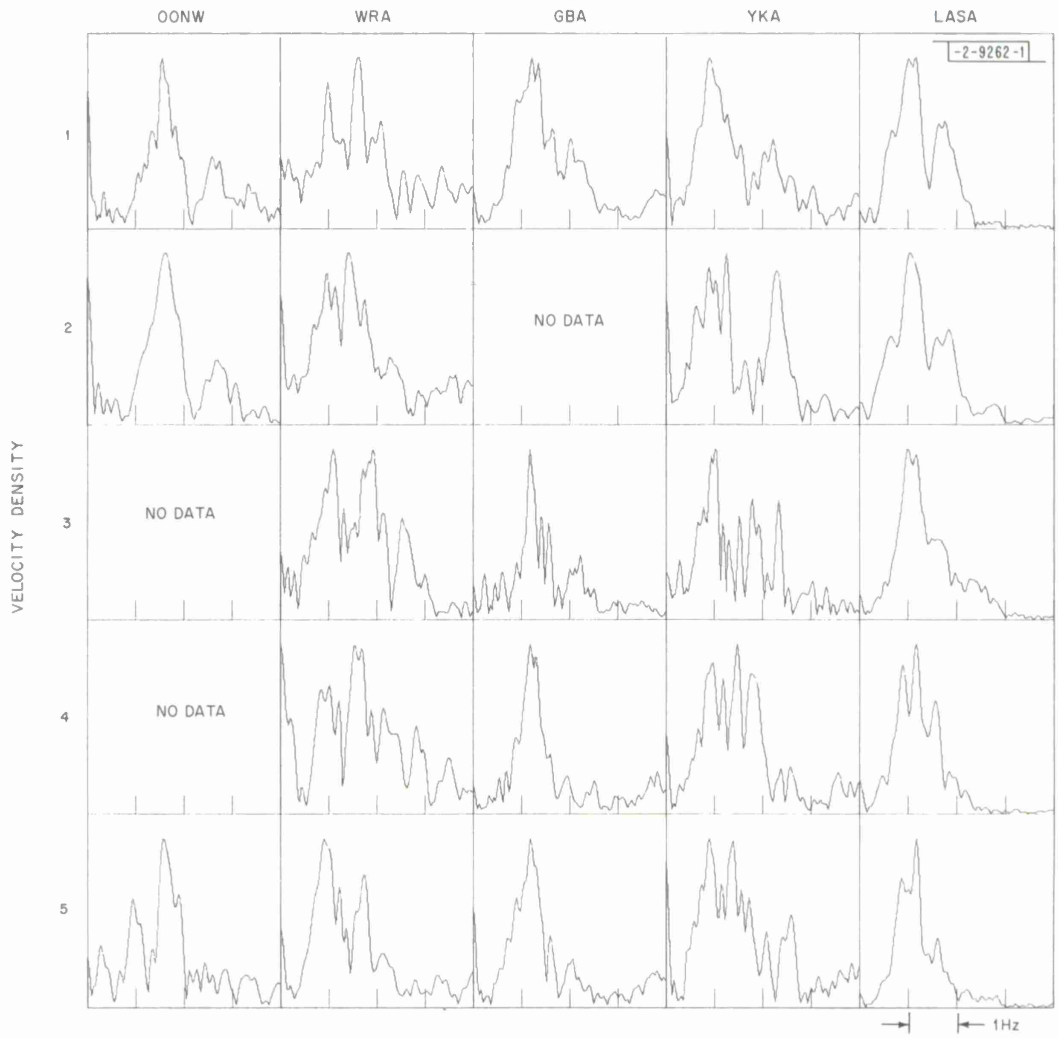


Fig. I-7. Normalized velocity spectra computed from 10 seconds of P-wave beam from five events in central Asia and recorded at five arrays.

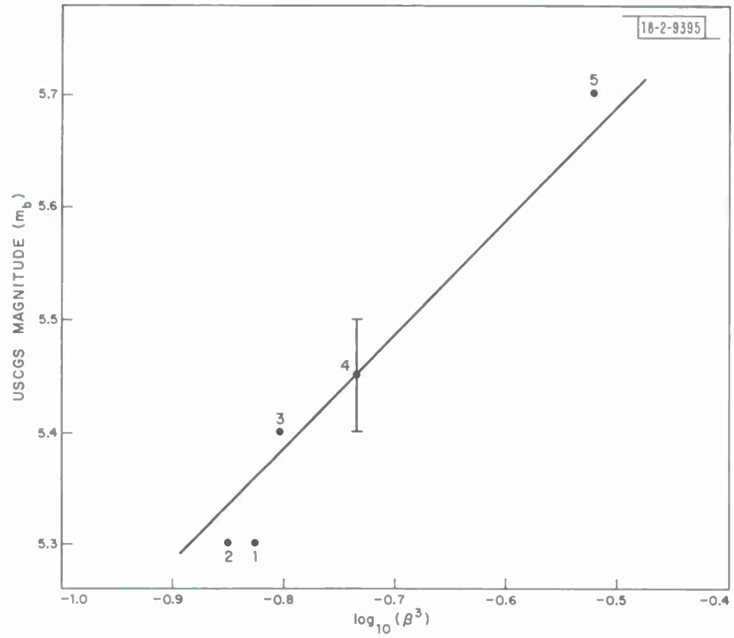


Fig. I-8. World-averaged $\beta$ plotted versus USCGS magnitude.

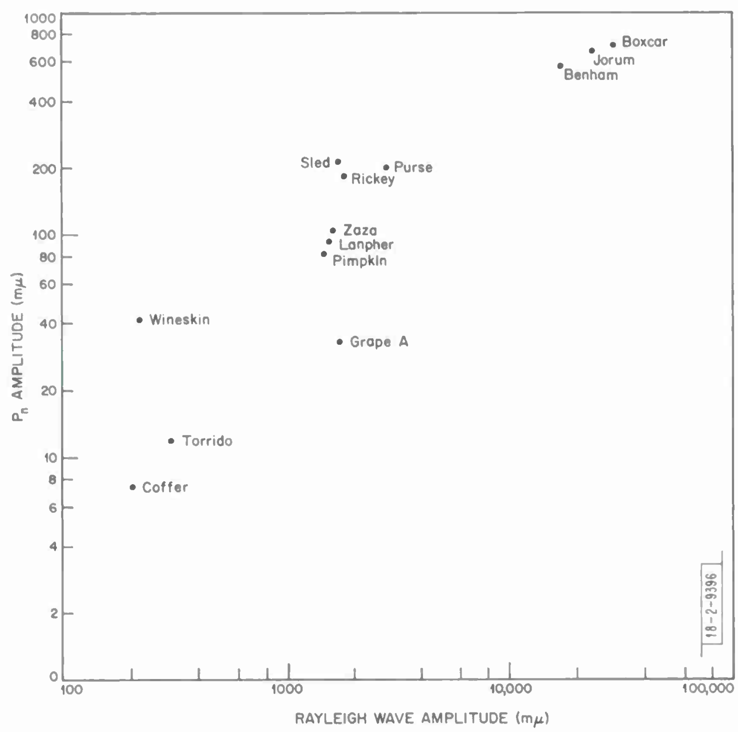


Fig. I-9. $P_n$ versus Rayleigh wave amplitudes from announced NTS explosions observed at LASA A$\phi$.

# II. PROPAGATION PATH

## A. SHORT-PERIOD SEISMOLOGICAL OBSERVATIONS AND LATERAL INHOMOGENEITIES IN THE MANTLE

In any effort to lower the discrimination threshold we need to understand influences which may degrade the character of the seismic signal, in particular such parts of the signal as may be used in routine measurements of signal parameters. An intensive study of propagation path effects, particularly near source effects, reveals that horizontal variations in elastic properties (e.g., plates underthrust at island arcs) have gross effects on short-period observations.

It is well known that Longshot, fired in the Aleutians, was mislocated by 25 km (epicenter) and 70 km (focal depth). Recently a technique for studying near-source inhomogeneities, the residual sphere,[1] was used on Longshot and demonstrated the clear role of the sub-Aleutian plate in generating this mislocation. Since then we have generated a large number of residual spheres in order to study island arc structures in general, and also the possibility of severe substation structure in certain circumstances. We conclude from a variety of techniques that horizontal velocity contrasts up to 10 percent for P-waves and substantially greater for S-waves exist in many island arc regions in the upper 300 km.

Perhaps more important than mislocation is the effect that these plates have on short-period waveforms. A comprehensive compilation of records from Longshot has recently been published[2] and a study of waveforms from this explosion has been completed. It reveals a quite remarkable variation in P-wave character. Even the relatively crude measure of magnitude shows structure much more variable than should be expected. Figure II-1 is an equal area projection of the focal hemisphere beneath Longshot. A symbol representing a magnitude determination is placed on the focal hemisphere at the appropriate azimuth and dip angle at which a ray emerges from Longshot to reach the station in question. The major fluctuations shown are entirely confined to the two northern quadrants and we infer that plate structure is producing major shadowing, multipathing and signal enhancement effects. Computer programs have been developed to trace rays in complex structures and see what generalizations can be made. Figure II-2 is a striking example of the variation in signal character for a slice through the focal sphere at azimuth 55° to 235°. Rays emerging near the plate dip angle show very large variations in signal amplitude and the signal at PG-BC (Prince George-British Columbia) is clearly a shadow zone effect. The excellent PcP signal at PG-BC confirms that near-receiver structure can have played little role in this phenomenon.

The variation in signal suggests that we should re-examine "complexity" determinations. A complexity computed from PG-BC was very large and by itself would have characterised the event as a palpable earthquake. The apparently complete suppression of the first arriving P-wave at PG-BC and several other stations places an unduly large emphasis on later arriving signal and may give the false impression that complexity comes from near-source reverberations or scattering when, in fact, such reverberations are no greater in "complex" than "simple" signals – only the first few seconds are different.

Figure II-3 shows a plot of complexity against magnitude for Longshot, and it is clear that a screening of records to accept only such signals as gave a magnitude greater than the mean would reveal an unambiguously low complexity. In a previous SATS (December 1969), Capon suggested that the value of minimum complexity was greater than that of complexity as a network average, and this idea is concordant with the suggestions made here.

Explosions from Novaya Zemlya have in the past revealed high complexities at many stations,[3] and we show in Fig. II-4 a similar plot to Fig. II-3 for a Novaya Zemlya event. The conclusion is that lateral heterogeneities may well exist beneath Novaya Zemlya, disturbing the P-waveform. The fact that the Urals and Novaya Zemlya were probably the locus of an island arc convergence followed by Himalayan style mountain building in Permian times may be important in considering present-day structure beneath the Urals axis.

D. Davies

Since the initial operation of the Montana LASA, considerable effort has gone into investigating the travel time anomalies of P-waves.[4,5] These anomalies have been used to infer the geological structure down to depths of 70 km directly beneath the array.[6] More recent investigation into these anomalies has been directed at determining the gross structures around the seismic regions at teleseismic distances from LASA.

This study concerns the values of the mislocation vectors for earthquakes recorded at LASA in 1969. These data consist of arrival times that were punched on cards as part of the daily operation at the array. These arrival times were used to locate the events without any station correction being introduced into the location. These locations were compared with the USCGS epicenters and the mislocation vectors were plotted on a map. In most cases the mislocations are smoothly varying over a seismic region and tend to be parallel to the direction of the azimuth to LASA. The consistency and smoothness of the error variation for Central America is illustrated in Fig. II-5. The cause of such an error can best be explained by an anomaly under LASA. Not all vectors in this region, however, are conformable to a simple pattern. The seismic region that is south of Honshu, Japan, clearly does not even exhibit the mislocation consistency seen in Central America. Figure II-6 shows the southern section of Kyushu, Japan, and the Bonin-Volcano-Mariana Islands arc region. Here the mislocation errors for Kyushu and for the southern Marianas are of equal magnitudes and plausibly have a sub-LASA origin. The area between these two regions exhibits an error that is very nearly perpendicular to the azimuth to LASA and is of a smaller magnitude. This regional error must indicate source region structure. With the use of additional regions and events, a clearer picture of the LASA anomaly will be available.

R. M. Sheppard

Several recent investigations indicate that the $M_s$ versus $m_b$ relation for both earthquakes and underground explosions from western North America is anomalous compared to the relation for events from central Asia. Differences in the straight line fit of the $M_s$ versus $m_b$ relation for the two regions exhibit roughly an upward shift of 0.8 to 1.0 in the $M_s$ value or a downward shift of 0.6 to 0.8 in the $m_b$ value for western North America relative to central Asian events.

A shift toward lower $m_b$ for events from western North America can be caused by regional variations in the seismic attenuation of the upper mantle which affects earthquakes and explosions alike. To determine the size of this effect the method of reduced spectral ratio as presented by Teng has been extended to short-period body waves and applied to five deep-focus earthquakes recorded at a pair of arrays. The arrays used are TFSO, LASA and NORSAR. NORSAR is chosen since it lies in a shield area very similar to central Asia. LASA and TFSO are chosen since they lie in the western United States, with TFSO nearer the Nevada Test Site.

The reduced short-period spectral ratio is defined as

$$S_{12}(f) = \log_e \frac{A_1(f)}{A_2(f)} \quad ,$$

where subscripts identify arrays. By taking the ratio the source function is removed except for effects of finiteness, allowing one to determine the differences in medium through which the waves pass to the two arrays. Since the events are deep, the waves pass through the low velocity zone only once and that passage is beneath the receivers. Furthermore, near-source reverberations are absent. Events equidistant from LASA and NORSAR were chosen to avoid the introduction of large corrections in the differential attenuation due to differences in source-receiver distance. The total amplitude attenuation of waves can be stated functionally as $\exp(-ft^*)$, where $t^*$ varies with the ray path the waves follow. The slope, $\delta t^*$, of the least squares fit to the reduced spectral ratio is a measure of the difference in attenuation of the two ray paths.

The average $\delta t^*$ for the three deep events recorded on the LASA-NORSAR station pair is $-0.97$, and for the two deep events recorded on the LASA-TFSO station pair the average is $-0.68$. If we specify the Q-model of the upper mantle from 50 to 750 km depth beneath one receiver, we can determine the consistent relative Q-models beneath the other two receivers. By taking the Q beneath LASA to be 75, consistent Q-models are a Q beneath NORSAR of 390 and a Q beneath TFSO of 175.

This variation in attenuation beneath LASA and NORSAR contributes a variation of $m_b$ for 1-Hz waves of approximately 0.4 and beneath TFSO and NORSAR of 0.15. Since Norway and central Asia are tectonically stable areas, we can expect the variations in $m_b$ due to differences in attenuation between central Asia and western United States to be comparable to those found between Norway and western United States. These results confirm that the effect of differences in attenuation on the value of $m_b$ accounts for a significant portion of the observed differences in the $M_s$ versus $m_b$ relation between the western United States and central Asia.

R. Ward
(M.I.T. Earth and Planetary
Sciences Department)

## B. SEISMIC RAY CALCULATIONS IN ARBITRARY HETEROGENEOUS MEDIA

Seismic observations are affected in several ways by regional variations within the earth, particularly in the upper mantle, and therefore it is important to be able to account for such effects. The problem of tracing rays through a sphere in which the velocity is an arbitrary function of position has been formulated and programmed for the PDP-7 and 360/65 computers. At present, travel times and ray paths can be calculated; the extension to the calculation of amplitudes is planned in the near future.

Among the potential uses of this program is the calculation of travel-time and amplitude anomalies at seismic arrays in terms of the crustal and mantle structure beneath them. Another use is the study of the effects of the deep structure of island arc regions on seismic waves. Figure II-7 shows the P-wave ray paths calculated for a simple model intended to approximate the conditions applicable to the nuclear explosion Longshot, fired on Amchitka Island in the Aleutians. An 80-km thick slab of high-velocity material dips at an angle of 45° beneath the island arc in the model. The maximum velocity contrast between the slab and the surrounding mantle is 10 percent, and the contrast decreases with depth and is negligible beneath about 300 km. As can be seen in the figure, such a structure will have a pronounced effect on the amplitudes of P-waves, focusing them in some regions and creating a shadow in others. The travel times, too, are affected, being about $2\frac{1}{2}$ seconds early for waves traveling straight down the slab.

Presently, ray calculations for more detailed models are in progress, as well as the collection of seismic data with which to test various structural models.

B. Julian

## C. ANALYSIS OF RAYLEIGH WAVE MULTIPATH PROPAGATION OBSERVED AT LASA

An investigation has been made of the multipath propagation of Rayleigh waves by using data obtained from the large aperture seismic array (LASA). The use of the LASA in conjunction with a high-resolution analysis technique[7] provides a greater angular resolution and accuracy than was previously possible for the analysis of the multipath propagation. Measurements have been made of this phenomenon for the Rayleigh waves of 26 events distributed at various azimuths and distances from LASA. On the basis of these measurements, reasonably good conjectures can be made concerning the actual propagation paths for groups in the 20 to 40 second period range. It has been observed that in almost all cases these propagation paths can be associated with refractions and reflections at the continental margins.

The angles of approach of the 20, 25, 33, and 40 second period groups were measured, using the high-resolution method, over four successive nonoverlapping 200-second intervals, starting at the onset time of the Rayleigh wave. Thus the group delay for the multipath arrivals will be known in multiples of 200 seconds. This information appears, in many cases, to be adequate for allowing a reasonably good conjecture to be made concerning the actual paths taken by the various group arrivals at LASA.

The propagation paths must satisfy Fermat's principle; that is, the ray path must be a stationary-time path. This means that for Rayleigh waves the paths for the initial group arrivals will be minimum-time paths, while later group arrivals propagate along paths which, while not minimum-time paths, are stationary-time paths. In addition, the propagation paths must satisfy Snell's law for refraction and reflection at boundaries across which there is a contrast in phase velocity. In terms of propagation of Rayleigh waves in the surface layers of the earth, these boundaries usually represent the continental margins.

Thus, when an angle of arrival is measured which differs from the true azimuth of an event, it is quite likely that this bending of the propagation path can be explained by the refractions and reflections which must take place at continental margins. However, in some cases the bending of the ray paths appears to be caused by other major tectonic features of the earth, such as ridges.

The initial groups will usually arrive at the true azimuth or at slight azimuthal deviations from this. Thus initially the path will consist of the great-circle path between the epicenter and LASA, or a slightly refracted version of this path. Once this initial path is known, the later paths can be obtained by choosing one which fits the path length difference condition and has an angle of approach at LASA which agrees with the measured angle.

Two examples of such propagation paths which were similar to, or typical of, the results for the rest of the 26 events analyzed are shown in Figs. II-8 and II-9. The map shown in these figures is an equidistant azimuthal projection with LASA as the projection point. Thus, on this map, all great-circle paths passing through LASA appear as straight lines and all points at the same distance from LASA project on a circle centered on LASA. The timing sequence for the group arrivals is not shown in any of these figures, for simplicity. In addition, two propagation paths whose azimuthal angles of arrival at LASA are within three degrees of each other are usually merged into a single path. All propagation paths in these figures are drawn as straight line segments, again for simplicity. In addition, all refractions and reflections are depicted as taking place at the geographic boundaries for the continents, although it is more likely to take place at the continental margins. The difference in positions of these two boundaries is in most cases very small and may be neglected.

The propagation paths for the 22 November 1966 Kurile Islands event are shown in Fig. II-8. We see that initially the longer period groups arrive at LASA along the great-circle path between LASA and the epicenter, or slightly refracted versions of this path. These groups are followed by shorter period groups which are refracted and reflected at the continental margin.

In Fig. II-9 we see the propagation paths for the 22 September 1967 central mid-Atlantic ridge. In this case the longer period groups arrive from an angle which deviates from the true azimuth by about ten degrees. It appears that these groups are guided by the mid-Atlantic ridge and then emerge from it at the point where the ridge makes a sharp turn away from the direction toward LASA. The shorter period groups do not appear to be guided by the ridge, but are refracted and reflected in the usual way.

It should be noted that reflection of a group usually takes place at a continent-to-ocean boundary and that the angle of incidence usually exceeds the critical angle for the period of the group. This result is to be expected, since it is at these angles of incidence that reflection of large amounts of energy would be expected. It should also be mentioned that the present results represent an extension of the work of Evernden[8,9] who also measured the direction of approach of Rayleigh waves.

J. Capon

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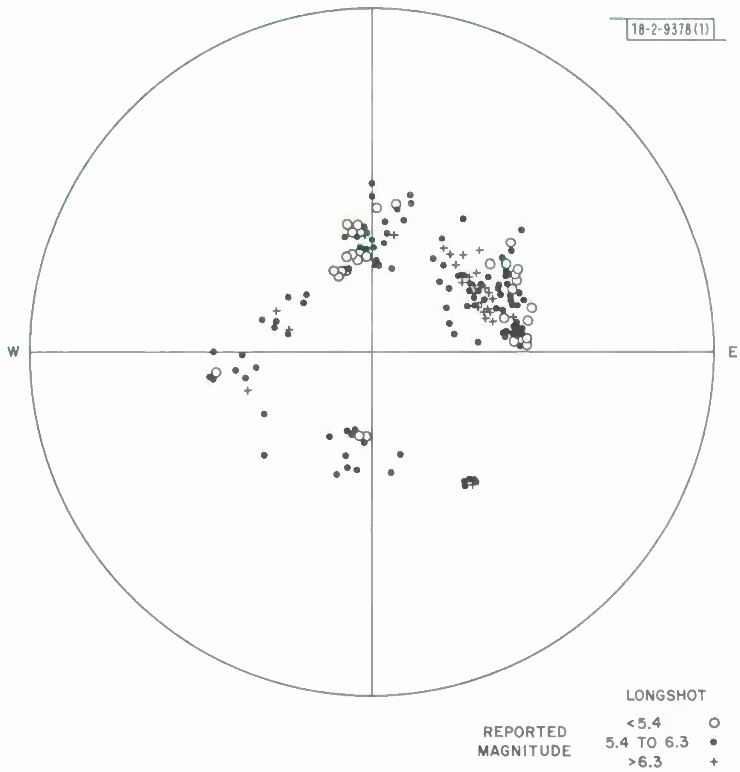


Fig. II-1. "Magnitude sphere" for Longshot. Reported magnitudes are identified by symbols at appropriate dip and azimuth for rays leaving Longshot to reach reporting stations. Lambert's equal area projection of focal hemisphere is used.

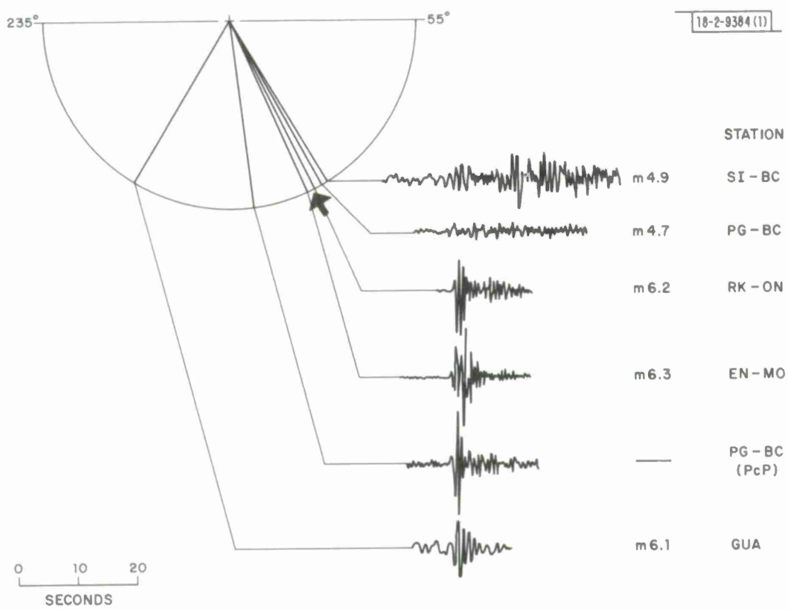


Fig. II-2. Signals from receivers in azimuths 55° to 235° shown at their positions on slice through focal hemisphere at Longshot. Aleutians plate dips at an angle indicated by bold arrow.

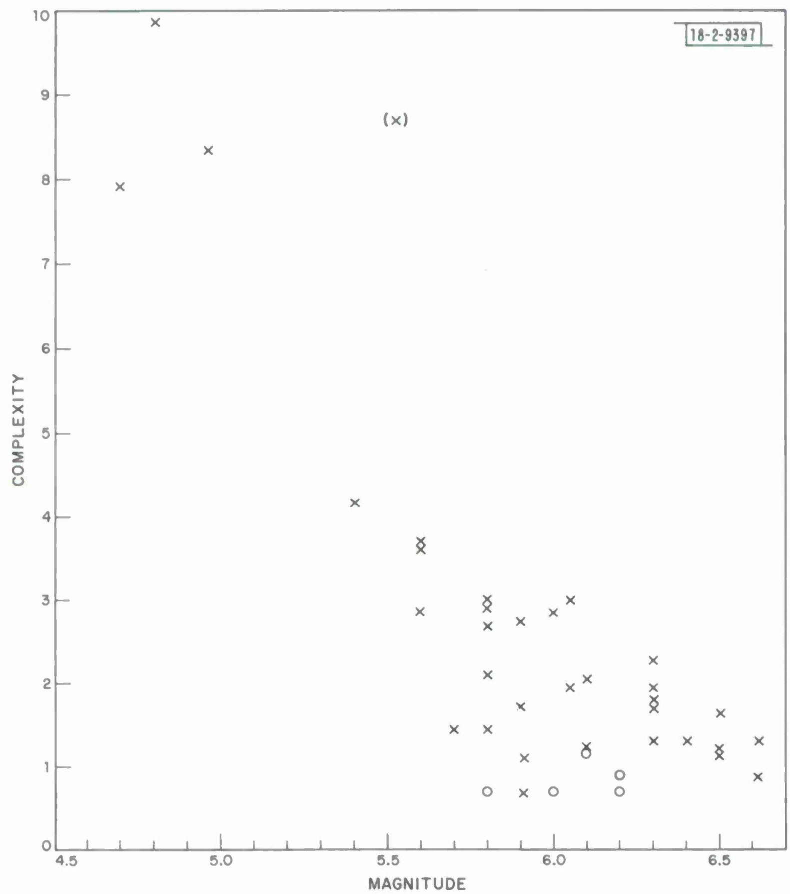


Fig. II-3. Complexity determinations as a function of reported magnitude from many stations for Longshot. Open circles represent arrays; magnitude of bracketed determination is suspect, since it is barely teleseismic.

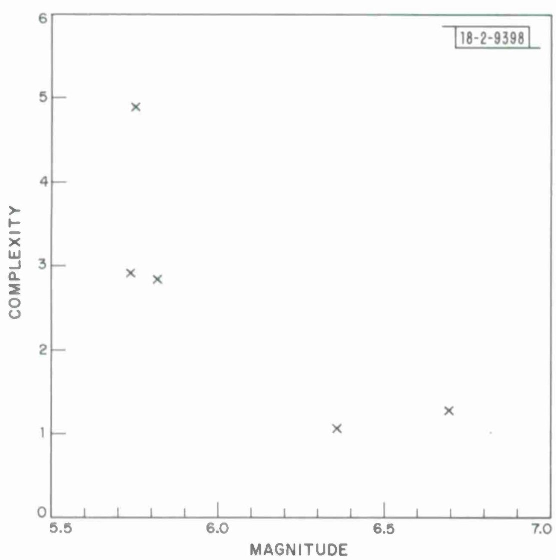


Fig. II-4. Similar plot to Fig. II-3 for few stations reporting a Novaya Zemlya event.

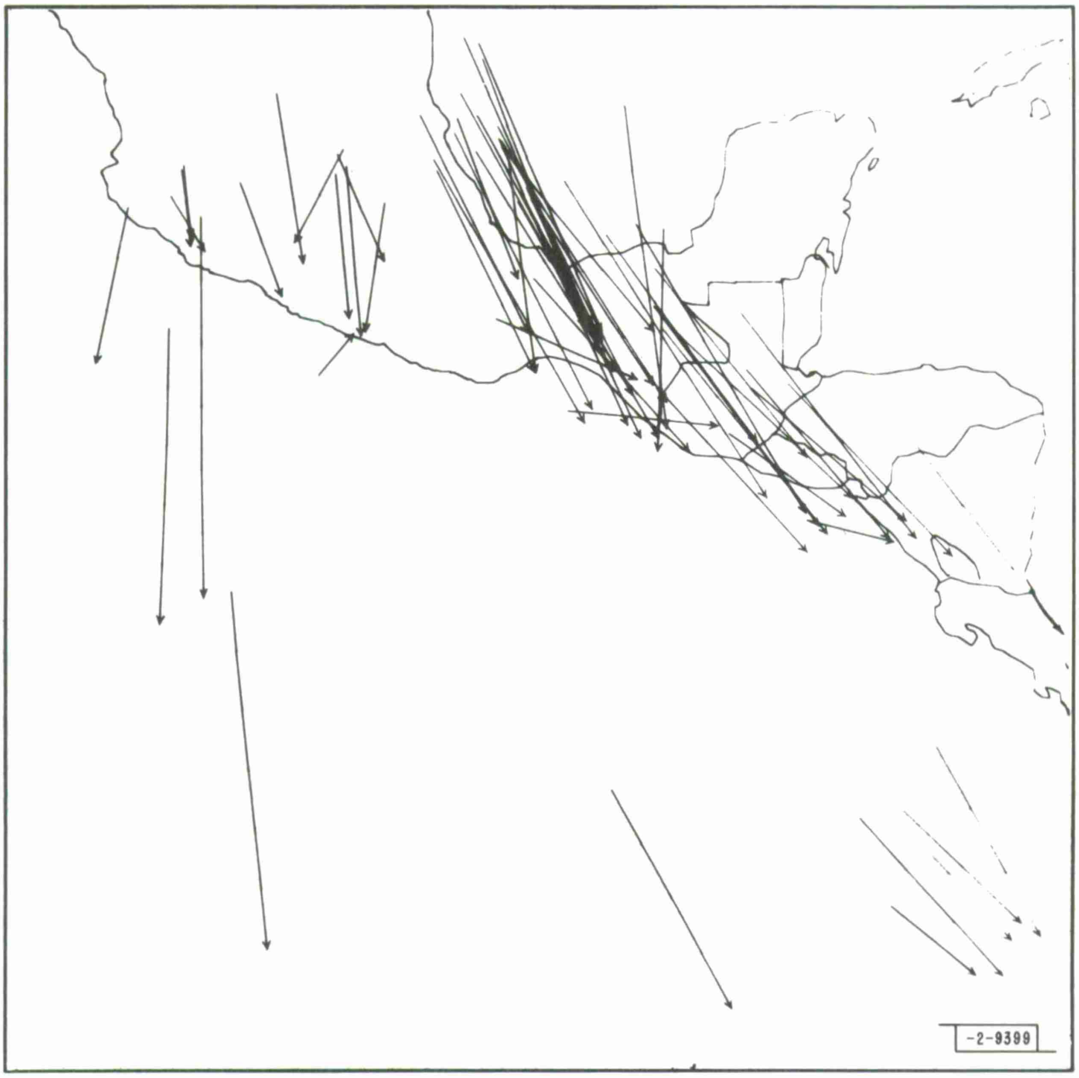


Fig. II-5. Mislocation vectors for Central America (the arrowhead is the USCGS location).

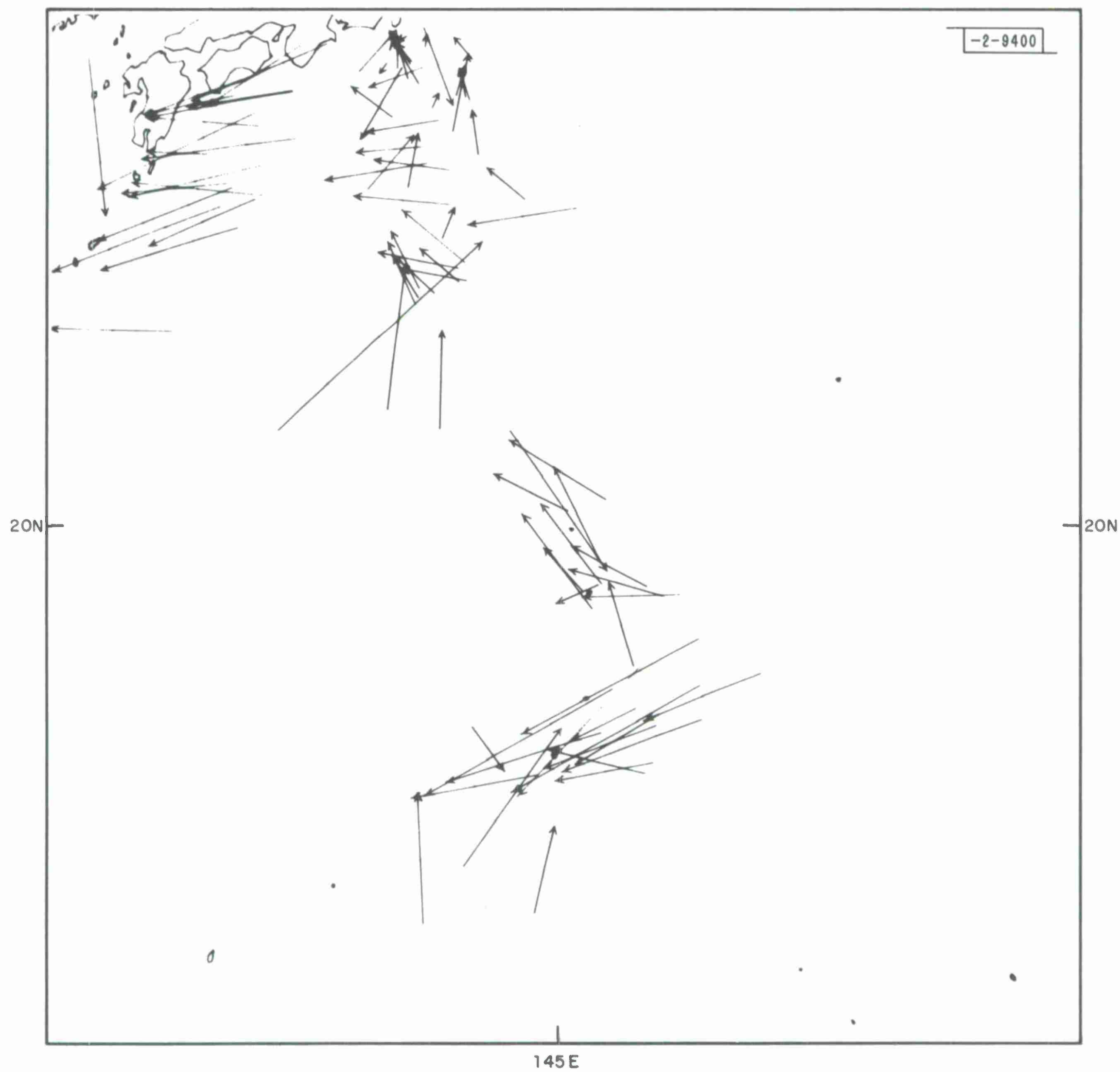


Fig. II-6. Mislocation vectors for Mariana Islands region.

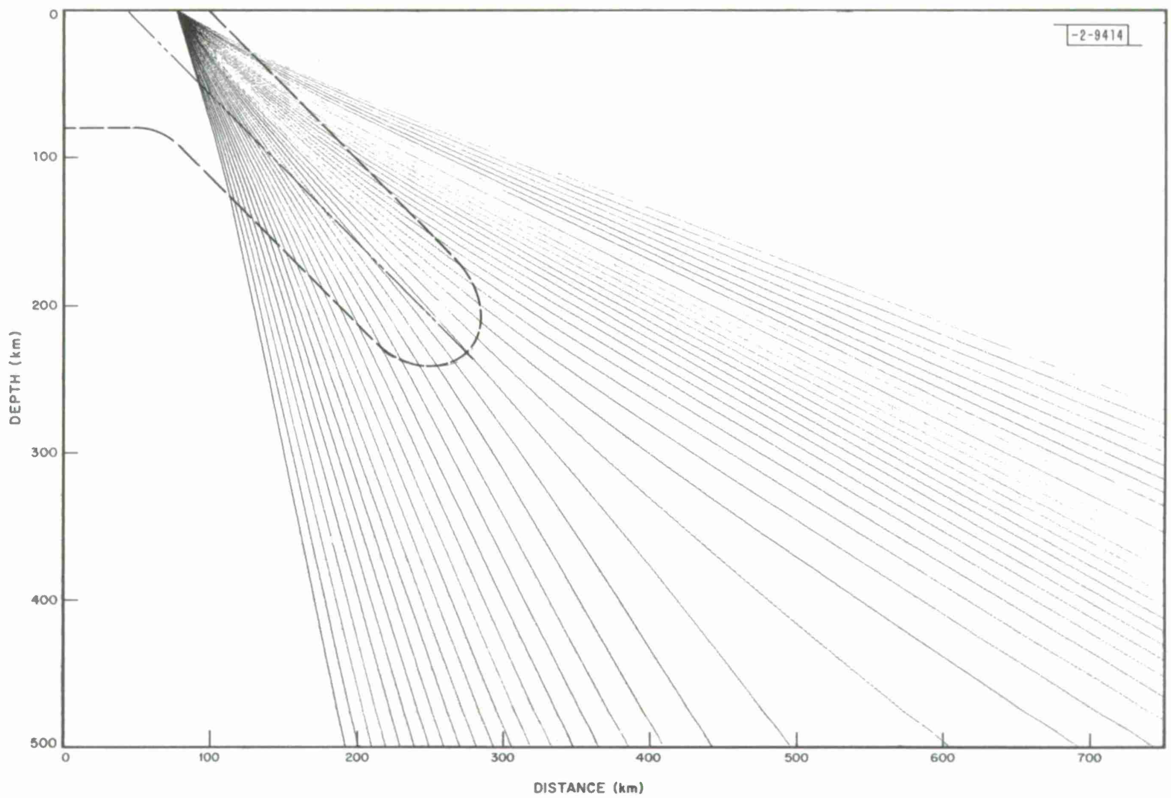


Fig. II-7. Ray paths calculated for simple model of seismic velocity beneath an island arc. High velocity slab 80 km thick extends downward at an angle of 45° to a depth of 200 km. Rays are spaced evenly at 1° intervals at focus. Note severe geometric spreading of rays traveling down the slab.

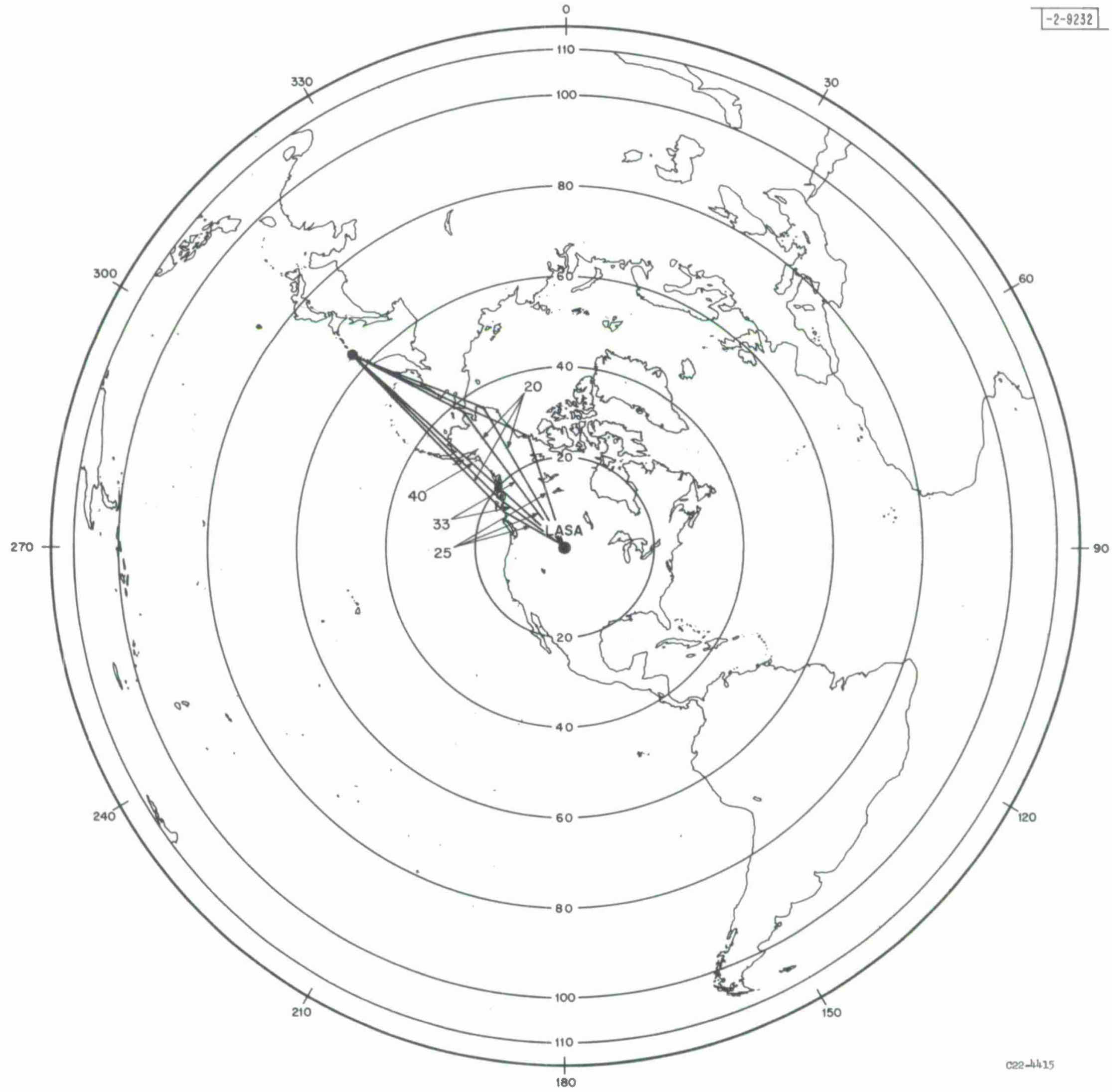


Fig. II-8. Propagation paths for 21 November 1966, Kurile Islands event.

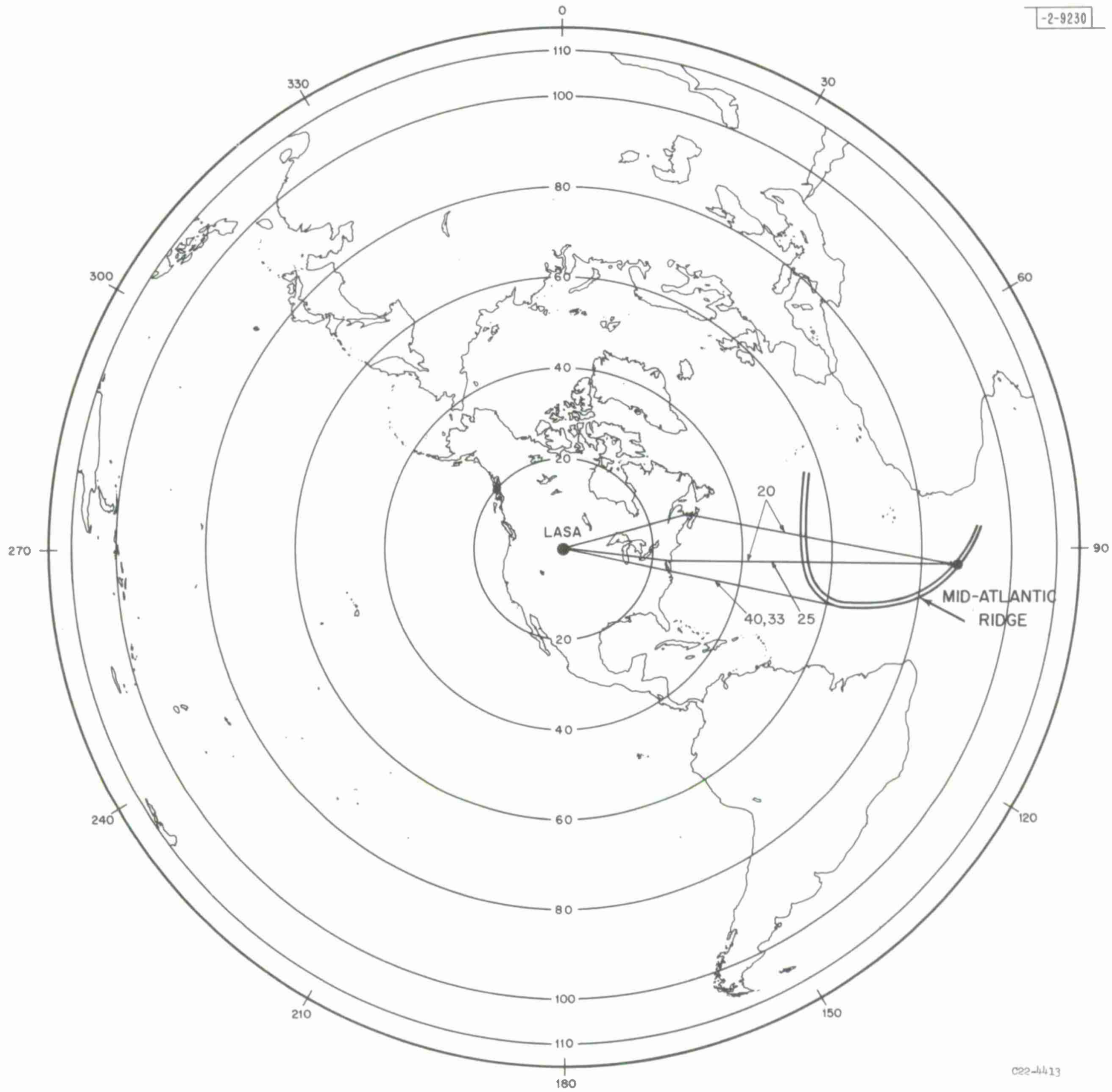


Fig. II-9. Propagation paths for 22 September 1967 central mid-Atlantic ridge event.

# III. ARRAYS AND ARRAY STUDIES

## A. MEASUREMENT OF FREQUENCY-WAVENUMBER SPECTRA AT NORSAR

The frequency-wavenumber spectra of the microseismic noise, in the 1 to 5 second period range, have been measured at the Øyer subarray at NORSAR. This subarray consists of about 12 short-period vertical seismometers located within an aperture of about 18 km. The high resolution method[1] was used in the measurement with a block length of 25 seconds, leading to a frequency resolution of 0.04 Hz, and with 36 blocks which yields 90-percent confidence limits of about 1.4 dB. In order to determine how the spectrum varies with time, the measurement was made on 6 noise samples taken every other month, so that an observation period of about one year was obtained.

The results of one of the measurements for a 1 December 1968 noise sample are shown in Figs. III-1(a-b) for frequencies of 0.2 and 0.4 Hz, respectively. The noise is seen to consist primarily of surface waves propagating from the northeast direction, with a phase velocity of about 3.5 km/sec. The measurements at other frequencies in the 0.2- to 1.0-Hz band indicated that there were large amounts of nonpropagating noise, relative to the amount of propagating noise. The result for this noise sample is typical of that obtained for the other noise samples.

These results are similar to those obtained recently by Bungum, Burland and Rygg,[2] who also used the high resolution method of measurement. These authors also show that the propagating noise at 0.2 and 0.4 Hz can be associated with low-pressure weather disturbances in the Baltic Sea.

J. Capon

## B. P-CODA AND UPPER MANTLE STRUCTURE

The program VESPA, described by Kelly in the June and December 1968 SATS, is being used to map the phase velocity structure of seismic signals from a number of presumed explosions from central Asia. These events are used in this initial study to minimize complications due to depth phases. Figure III-2 is an example of a vespagram from an eastern Kazakh event in which power is contoured (in decibels down from a peak power) as a function of arrival time and slowness. The vespagram of the figure shows well-defined arrivals within the P-coda up to 70 seconds after the initial P and, as pointed out by Kelly, at about the same velocity as P. The times of these arrivals, which are common to many events from this source region, are about +20, +40, and +65 seconds after P. P and these arrivals are marked by arrows 1 to 4 in the figure. Because all these arrivals are of about the same amplitude (22 to 26 dB down), we prefer to reject the notion that they are multiple reflections from the same boundary and interpret them as indications of separate reflections ("peg-legs") from different boundaries. The time of two of these arrivals shows rather good agreement with two boundaries within the upper mantle proposed by Johnson.[3] These boundaries are the top and bottom of a low velocity P-layer in Johnson's model based on western United States $dT/d\Delta$ data. The +20-second arrival is consistent with a reflection from the top of this channel, the +40-second arrival is consistent with a reflection near the sharp increase in the velocity gradient at the bottom of this layer.

Of course, other physical models could also explain these arrivals and at present we are not able to isolate the features to the receiver, rather than the source, region, but this will soon be feasible. The possibility of misidentification of depth phases as mantle reflections and *vice versa* should not be overlooked in seismic discrimination.

J. R. Filson
D. Davies

## C. AMPLITUDE AND TRAVEL TIME ANOMALIES OF CORE PHASES RECORDED AT LASA

A study is in progress of the variations of amplitude and travel time anomalies of core phases recorded at the subarrays of LASA. Thus far, 18 PcP events have been studied from the Gulf of Alaska, the Aleutians, northwest of the Kuriles and Kamchatka. Preliminary results show that amplitude and time anomalies for PcP events are very consistent and slowly varying for $\Delta \sim 20°$ to $65°$ along the northwest direction from LASA. This seems to indicate that crustal and upper mantle structure under LASA produces the observed subarray anomalies rather than source region effects. This has been verified in a few isolated cases by studying PKP events which sample the same upper mantle structure and crust under LASA as PcP events from the Aleutians.

Data from other azimuths are being studied. A forthcoming technical note will give the results of this work in detail.

C. W. Frasier

## D. SIGNAL COHERENCE AT LASA

Frequently we observe gross signal character fluctuations across LASA and the variation in arrival time residuals is well known.[4] To what extent is the coherence or lack of it across the LASA aperture source generated or receiver generated? Signal generated noise has often been observed at arrays[5] and a question of importance is whether signal variations across LASA are due primarily to such noise generated beneath or near the array. We have started a survey of coherence and the results presented here are purely qualitative. They do, however, give an indication of sources of variation in signal across the array. We have already noted in a previous section the value of Longshot for studying mantle structure and Fig. III-3 shows a selection of channels recorded at LASA from the P-wave from Longshot. Figure III-4 shows the same channels recording PcP from the same event at the same gain.

PcP from Longshot seems a relatively simple event, but P from Longshot contains extensive incoherent coda. We believe that this latter is therefore associated with near-source structure that P-waves but not PcP waves encounter *en route* from Longshot to LASA (see Sec. II-A-1). A program of coherence studies is planned in order further to evaluate array capabilities.

D. Davies
J. Capon

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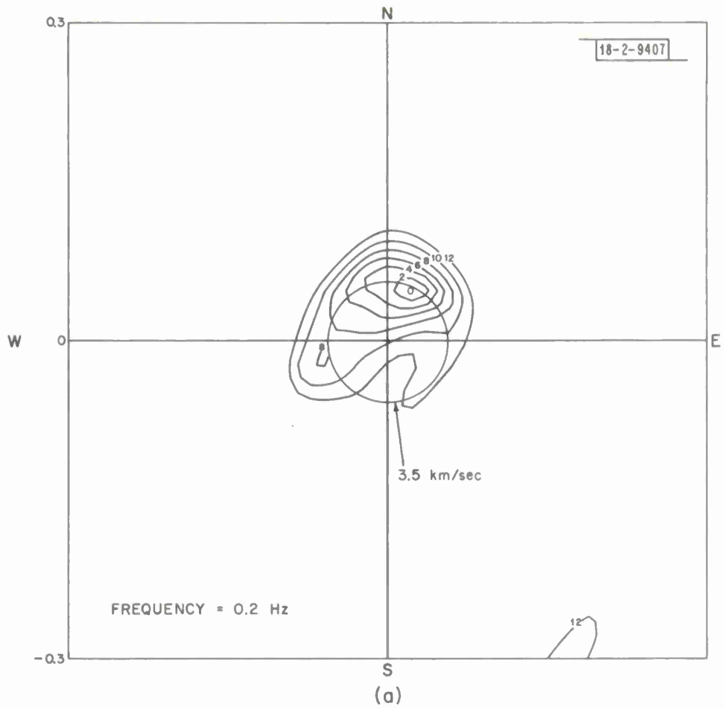


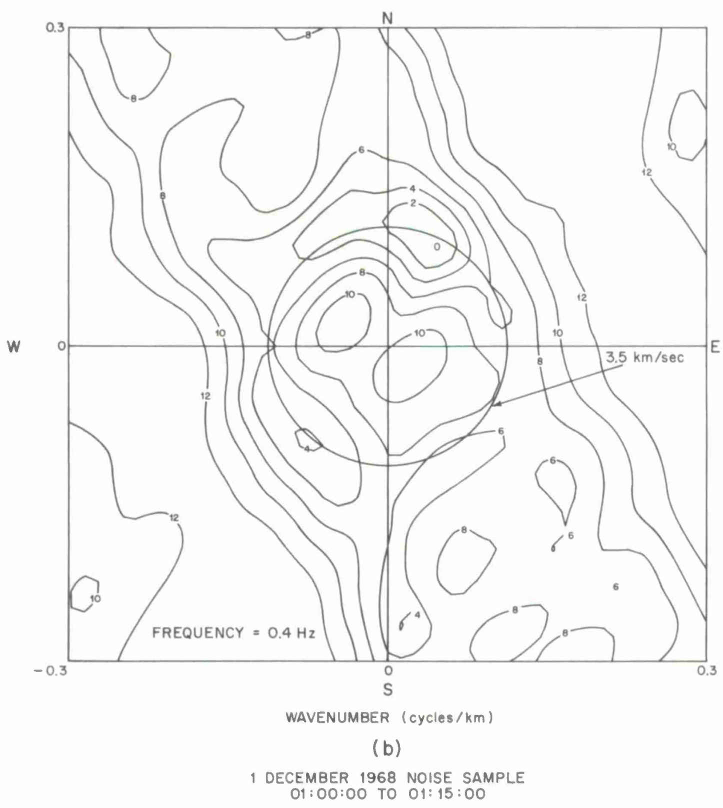


Fig. III-1(a-b). High resolution frequency-wavenumber spectra for short-period microseismic noise at the Øyer subarray at NORSAR.

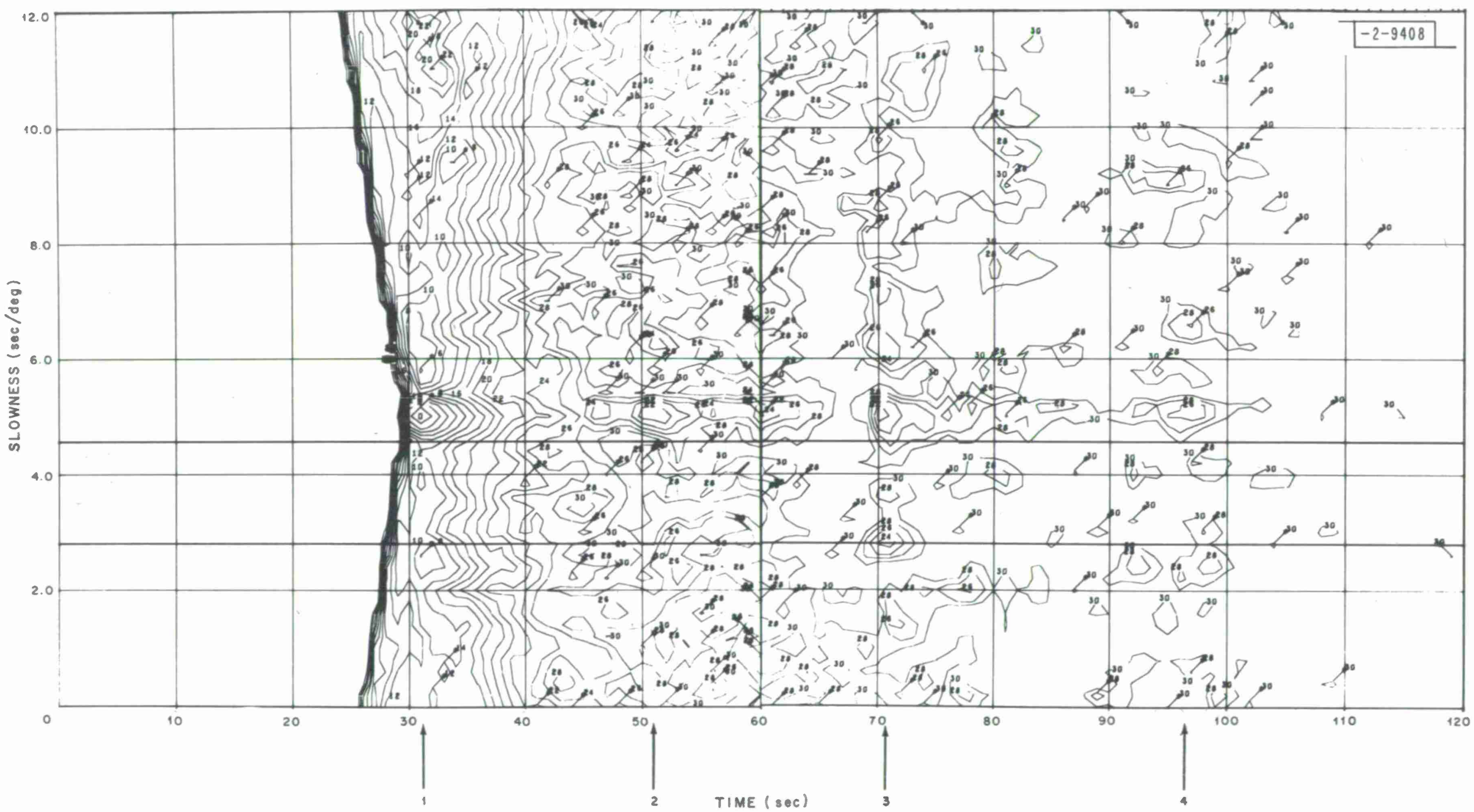


Fig. III-2. Vespagram of eastern Kazakh event showing discrete energy arrivals for more than one minute after event.

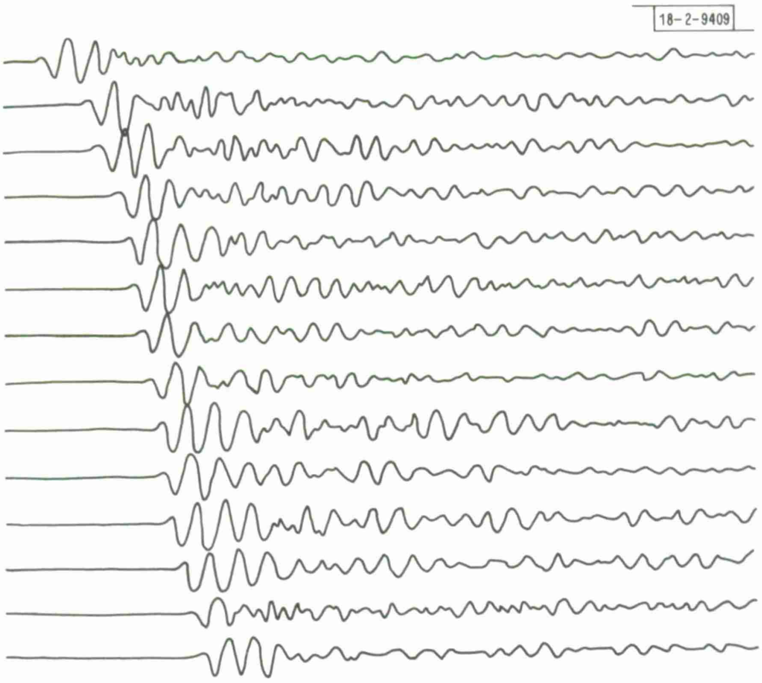


Fig. III-3. Display of seismograms of Longshot across LASA. Note P-wave is followed by very complex coda.

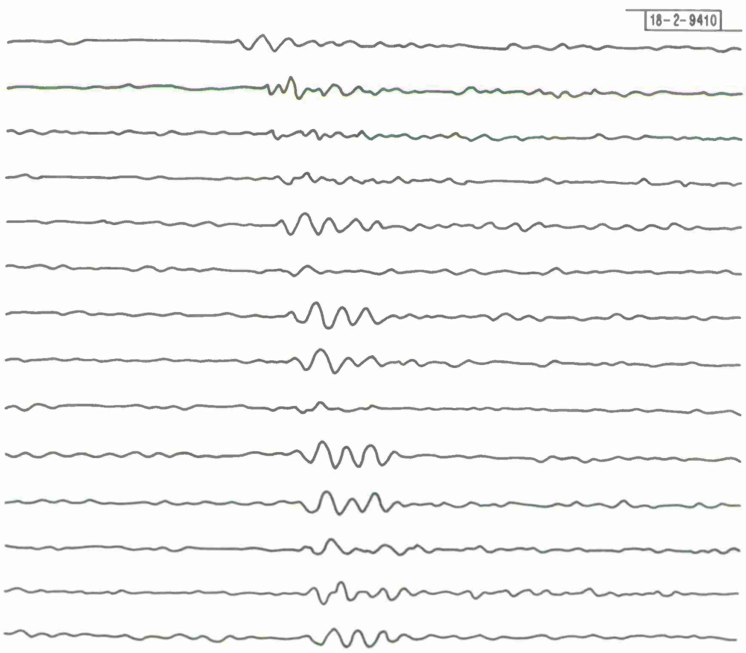


Fig. III-4. PcP for Longshot, same gain settings as for Fig. III-3. Note relatively isolated pulse.

# IV. SIGNAL ANALYSIS AND DATA FACILITIES

## A. DATA FACILITIES

The seismic data library now consists of over five thousand events identified and located by USCGS and a comparable number of events not so identified by USCGS. Because of its vast size, the library is being edited so that many pre-1968 events are being released to accommodate more recent data. Because of the long retention period of seismic data by SAAC, it is possible to request data for almost any time period during the last twelve months. We are now selectively collecting approximately five hundred events for 1969 and will continue at this yearly rate in the future.

Our digital recordings of NORSAR data are not as comprehensive as may be necessary for experiments involving large numbers of events or events of special nature. To correct this situation, we are requesting NORSAR data on a weekly basis. By using the Montana LASA as a basis for our request of NORSAR data, we have collected several hundred events that were recorded in the interim NORSAR recording mode. In this format one single short-period sensor from each subarray is recorded on a digital tape.

To supplement digital data from the two large arrays for special studies and experiments we have obtained, and will continue to obtain, digital data from the United Kingdom arrays. In an analog sense, we are maintaining a continuous develocorder and helicorder recording of ten channels from LASA; A0, the D and F ring sum channels plus a long-period vertical seismometer. These records are scanned daily and the time picks made from the recordings are input into a location program to produce a daily seismic bulletin. This bulletin is used as a basis for data request of NORSAR data.

The analog library will be dramatically increased by our recent standing order for 70-mm film chips of all worldwide standard stations. These data will form the basic analog data set to be used for all our future studies.

R. M. Sheppard

## B. PDP-7 DATA PROCESSING FACILITIES DEVELOPMENT

The FORTRAN IV compiler has been completed in its final form on the drum and has been in extensive use for several months. This usage has uncovered several "bugs" which have been corrected. Many subroutines have been added to our library, two of which are particularly important from the users' point of view: an input/output package that allows one to read and write magnetic data tapes in any of the standard LASA formats; and a display package to show visually data and/or alphanumeric characters. Both of these subroutines are called and used in the same manner as the corresponding IBM machine language library subroutine in the 360 system. Thus old programs which ran on the Lincoln or M.I.T. Computation Center IBM systems can run here with no essential reprogramming changes – only changes due to our much smaller core memory size are necessary. Hence this system, including the Editor, has become a very popular, viable and useful tool and is resulting in a substantial financial saving.

The new Data Analysis Console has been completed. Its concept and function are the same as the old Analysis Console,[1] but it has several important advantages:

(1) There is provision to read in (and operate upon) several data tapes (e.g., from different sites) and align different times from the different tapes together.

(2) The data are all read into and stored on the drum. Thus, the tape drives are used only during the initialization and are free thereafter. The programs, likewise, are permanently stored on the drum instead of a magnetic tape. This replaces the virtual infinite memory with a large finite data base of up to 32 channels.

(3) The whole system operates as a foreground program with the data link time-shared to the IBM 360 operating in the background. Thus, when long jobs are being processed at the M.I.T. Computation Center, one can use the new Console at will – i.e., a computer is not tied down for long routine processing.

(4) The old "Constants" program has been combined with the new "Display" program.

(5) The reference is stored on the drum and the whole system is organized to permit ease of operating on the reference by any programmer writing in FORTRAN and storing his results in COMMON where the new Console can operate and/or display it.

P. L. Fleck

## C. PROBABILITY DISTRIBUTIONS FOR ESTIMATORS OF THE FREQUENCY-WAVENUMBER SPECTRUM

In a recent paper[2] the conventional and high-resolution estimators for the frequency-wavenumber power spectrum were discussed. The probability distributions for these estimators were derived using approximations recommended by Blackman and Tukey.[3] However, it is possible to show that these probability distributions can be derived precisely by using some results due to Goodman.[4] Thus, using these results it has been shown that the conventional estimator $\hat{P}(\lambda, \underline{k})$ is a multiple of a chi-square variable with 2M degrees of freedom, and mean variance given by

$$E\{\hat{P}(\lambda, \underline{k}_o)\} = \int_{-\pi}^{\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(x, \underline{k})\,|B(\underline{k}-\underline{k}_o)\,W_N(x-\lambda)|^2\,\frac{dx}{2\pi}\,dk_x dk_y$$

$$\mathrm{VAR}\{\hat{P}(\lambda, \underline{k}_o)\} = \frac{1}{M}\,[E\{\hat{P}(\lambda, \underline{k}_o)\}]^2$$

where $P(\mathbf{x}, \underline{k})$ is the frequency-wavenumber power spectrum, $|B(\underline{k})|^2$ is the beamforming array response function defined in Eq. (15) of Ref. 1, and $|W_N(x)|^2$ is the Bartlett frequency window defined in Eq. (14) of Ref. 1. It is interesting to note that the result for the distribution of $\hat{P}$ is essentially the same as that given in Ref. 1 using the approximations recommended by Blackman and Tukey.[3]

It has also been shown that the high-resolution estimator $P'(\lambda, \underline{k})$ is a multiple of a chi-square variable with $2(M-K+1)$ degrees of freedom and mean variance given by

$$E\{P'(\lambda, \underline{k}_o)\} = \frac{M-K+1}{M} \int_{-\pi}^{\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(x, \underline{k}) \, |B'(\lambda, \underline{k}, \underline{k}_o)$$

$$\times W_N(x-\lambda)|^2 \frac{dx}{2\pi} dk_x dk_y$$

$$\mathrm{VAR}\{P'(\lambda, \underline{k}_o)\} = \frac{1}{M-K+1} [E\{P'(\lambda, k_o)\}]^2 \quad ,$$

where B' was defined in Eq. (22) of Ref. 2.

The result for the distribution of P' given here should be compared to that derived in Ref. 2, where it is shown that P' is a multiple of a chi-square variable with 2M degrees of freedom. Thus, if $M \gg K$, both results yield essentially the same answer. However, the present result shows that P' is a biased estimator and that as a consequence we should take $[1/(M-K+1)]$ P' as an unbiased estimator. If power estimates are normalized with respect to peak power, as is usually done, then this correction for bias is not necessary.

These results have been presented in a manuscript[5] which has been accepted for publication in the Proceedings of the IEEE. We mention finally that a similar computation for the distribution of P' has been given recently by Burg.[6]

J. Capon

## D. POWER SPECTRAL DENSITY ESTIMATION

Many standard computational methods are now available for estimating the power spectral density of a sampled random time function. All these usual methods have associated with them window functions which are independent of the data or of the properties of the random process under study. We are now completing a study of the properties of some alternative methods of spectral estimation which do adapt to the properties of the random process. These are the maximum entropy method (MEM) developed by J. P. Burg[6] and a maximum likelihood method (MLM) adapted from Capon's[2] high-resolution method of wavenumber analysis. A detailed report of this work is now in preparation. An investigation of potential applications to the study of the frequency content of seismic events and codas is now in progress.

Figure IV-1 demonstrates some of the properties of various estimating methods. Eleven samples of an exactly known correlation function were used. The true spectrum was that corresponding to unity power white noise plus sine waves at 0.15 and 0.2 Hz. The power in the sine waves was 5.33 and 10.66 units, respectively. Each spectrum has been normalized to its peak value in Fig. IV-1. The spectral peaks cannot be resolved by a Bartlett window. The MLM has just barely resolved the two peaks. The relative power in the two peaks is correctly indicated by the peak values of the MLM spectrum. The peaks are well resolved by the MEM but the peak at 0.15 Hz is down 6 dB rather than 3 dB. However, the lower peak is somewhat broader and a numerical integration shows that the ratio of powers in the two peaks is 3 dB, the correct relative power in the two sine waves. In general, this is typical of MEM and MLM when applied to spectra with extremely narrow spectral peaks. That is, power is reflected by the peaks in MLM spectra, as it is for conventional methods, and by the area of the peaks of MEM spectra. All methods tend to show true spectra when the peaks of the true spectra are broad with respect to the ability of the particular method to resolve them.

The effect of small perturbations of the correlation function has been experimentally investigated by adding a small amount of noise to exactly known correlation functions. Perturbations of the spectra are comparable for the conventional Bartlett spectrum and MLM but the perturbation of the MEM was somewhat larger. However, neither MLM or MEM were unduly sensitive. Preliminary applications to actual seismic data, using measured correlation functions, corroborated this conclusion.

R. T. Lacoss

The conventional estimate of the energy density spectrum of a transient seismic event, at a single station, is defined as the magnitude squared of the Fourier transform of the observed waveform. This estimate of the energy density spectrum has a bias equal to the power density spectrum of the background noise. Consequently its accuracy is low when the signal-to-noise ratio is small. It is desirable to design an estimator which exploits the noise characteristics and has a better accuracy. A simple estimator which has a considerably smaller bias and a higher accuracy in the low signal-to-noise ratio region has been introduced and its statistics have been studied. The statistics of estimates of the energy in a band of frequencies and of the ratio of such estimates have been investigated both theoretically and experimentally. From this investigation one can conclude that the identification threshold using short-period spectral information may be lowered slightly by the application of this estimator.

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## E. BEAMFORMING PROGRAM

POWER, a program which forms a maximum of 100 beams and prints out the average power for each beam, is now operational on the PDP-7 computer. The short period channels on LASA low-rate tapes are the input data used. Before beamforming, the data channel is filtered by three synchronous poles, each one passing 1.0 to 2.0 Hz. This yields an overall passband from 1.164 to 1.664 Hz and is similar to the filter used in the LASA on-line event detector. Since the coefficients are input parameters, they may be changed if different filters are desired.

The program checks for any bad data channels and deletes these from the beams, and also adjusts for glitches in the data. The parameters for each beam may be input directly as azimuth and horizontal phase velocity, or as latitude and longitude, from which azimuth, and distance are computed. The program will then compute the delays for each beam. The average powers will be output at time intervals specified by the user, along with a running average for each beam. We hope to use POWER for the investigation of very low level seismic disturbances that may be associated with seismic regions of the earth but which could never be described as discrete events.

Currently, VESPA, the velocity spectral program which runs on the IBM-360 computer, is being rewritten for the PDP-7 computer facility. This means that VESPA, which has proved to be a valuable analytical tool, will be accessible to more users, without the long turn-around time and high cost of the IBM-360 facility.

L. T. Fleck

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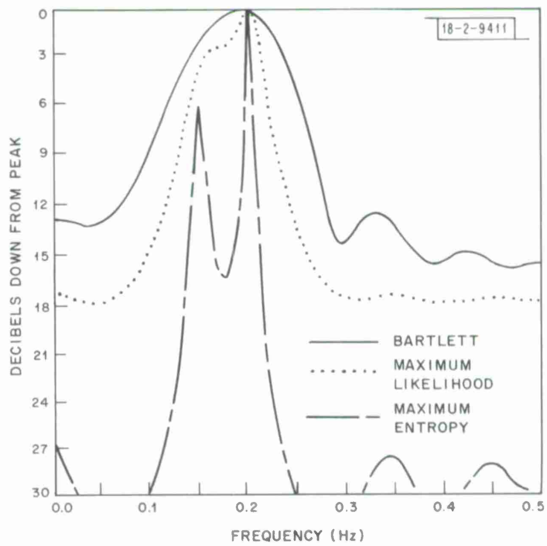


Fig. IV-1. Spectra obtained from correlation function $\rho_n = 1 + 5.33 \cos(0.3\pi n) + 10.66 \cos(0.4\pi n)$, $n = 0, \ldots 10$ using three different estimation algorithms.

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